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4TH INTERNATIONAL WORKSHOP ON WAVES, STORM SURGES, AND COASTAL HAZARDS
Incorporating the 18th International Waves Workshop

Assessing the Impact of Tropical Cyclone 'Rainfall' on Coastal Compound Flooding

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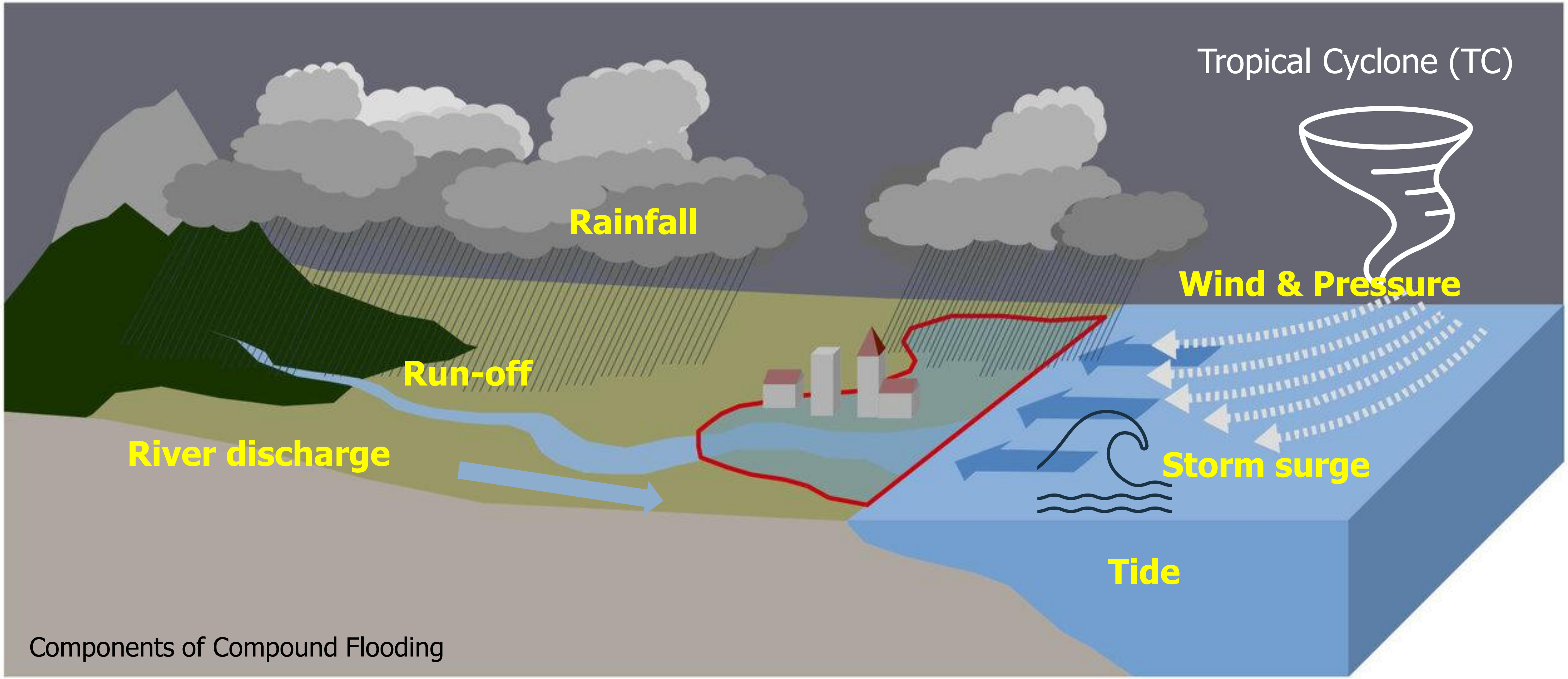
Introduction

Compound flooding considers the joint impacts of marine and hydrological interactions and has been identified as an international research priority (Zscheischler et al., 2018).



Components of Compound Flooding

(by Bob Yirka , Phys.org)

TC Rainfall Model?

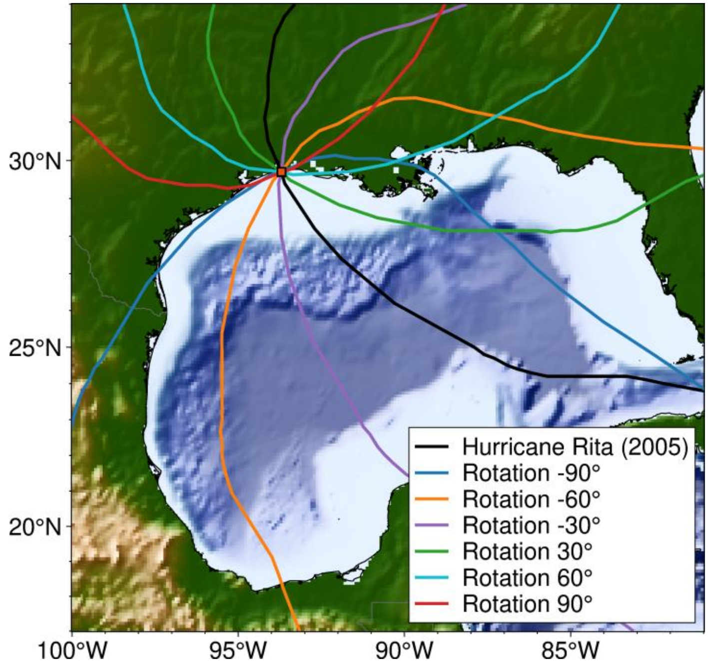
Then, how can we generate/estimate the TC rainfall (TCR)?

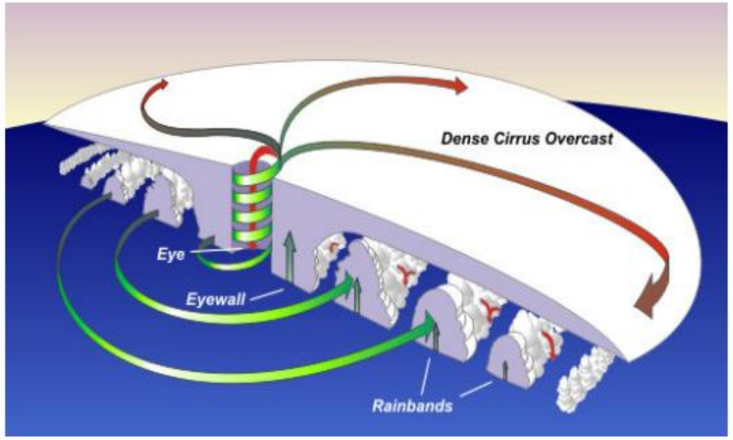
TC characteristic → ? → TC rainfall field → Runoff

Holland Model:
Reproduce using simple parametric relations

TC characteristic → Wind and pressure field → Storm surge

Parametric rainfall model





NWS JetStream Tropical Cyclone Structure

TC Rainfall Model

Existing parametric rainfall models : R-CLIPER (2003), IPET(2006), PHRaM (2007)…

Model	Precipitation training data	Authors	Pros	Cons
R-CLIPER 2003	TRMM TMI	Marks & DeMaria; Tuleya et al	- Little input variables needed	- Underestimates rainfall
PHRaM 2007	TRMM TMI	Lonfat et al	- Considers orographic lift - Considers assymetry	- Underestimates rainfall
IPET 2006	TRMM	US Army Corps of Engineers	- Very simple - Considers assymetry	- Overestimates rainfall
MRS 2009	TRMM PR	Langousis and Veneziano	- Good results over ocean	- Only valid over the ocean
Snaiki and Wu 2018	TRMM	Snaiki and Wu	-Good results -Attempts to incorporate rainbands	- Not fully parametric, part physical
Bader 2019	Qscat R	Bader	- Little input variables needed - Provides an uncertainty range	- Overestimates rainfall - Unable to capture spatial and temporal variability

A stochastic, observation-based parametric rainfall model (D.J. Bader, 2019)

$$I_g(R) = \left(i_{max} * \frac{\left(\frac{RMW}{R}\right)^{b_s}}{\exp\left(\left(\frac{RMW}{R}\right)^{b_s}\right)} \right)^{x_n}$$

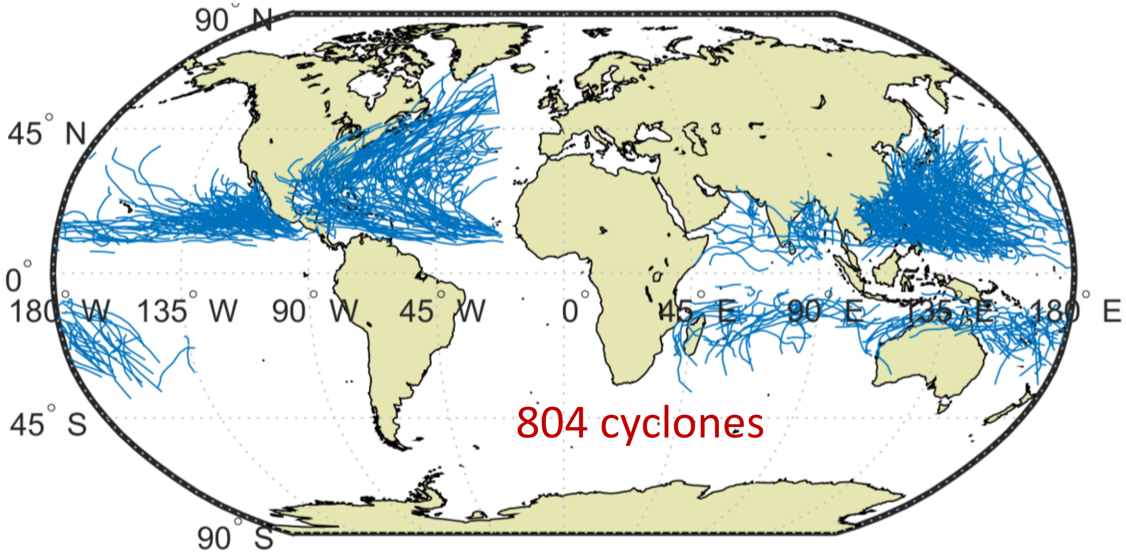
max. rainfall intensity (observation oriented)

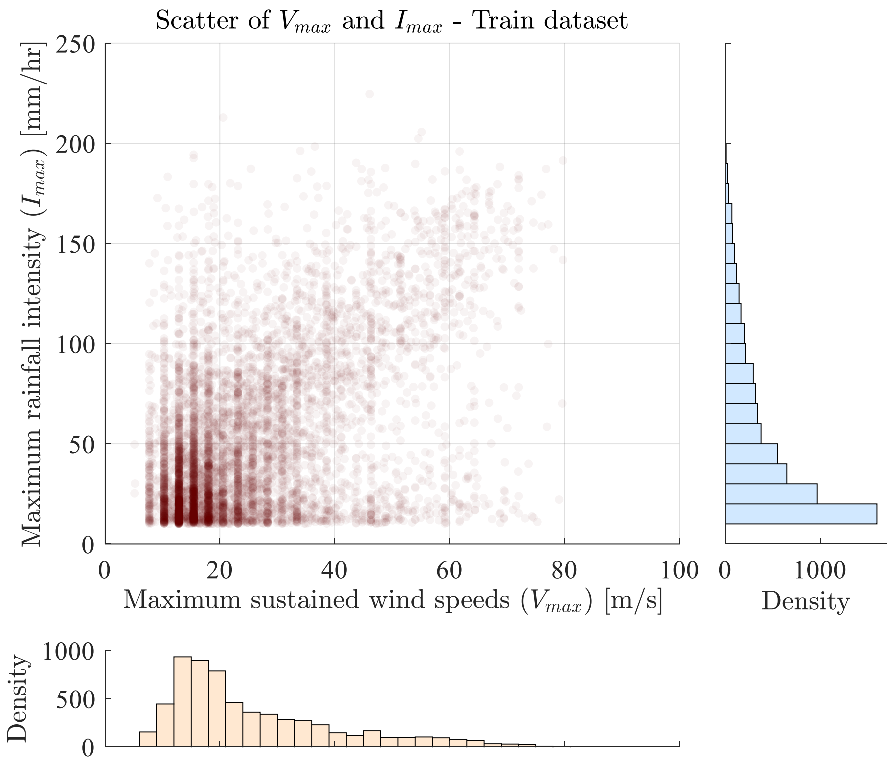
Objectives :

- Stochastically generates the TC rainfall distribution using an improved parametric TCR model with the consideration on the relation between wind speed and rainfall.
- Simulates a model TC to investigate the impact of TCR motion on compound flooding

TC Rainfall Model: How to determine imax

DATASET : QSCAT-R (THE QUIKSCAT TROPICAL CYCLONE RADIAL STRUCTURE DATASET 1999-2009)





Correlation metrics (imax)	vmax (max. wind sp.)	Latitude	Longitude	Translation speed	Pressure
Kendall's Rank	0.2687	-0.034	0.1058	0.0128	-0.2871
Spearman's Rank-Order	0.3798	-0.0513	0.1584	0.0192	-0.4049
Pearson Product Moment	0.4855	-0.0481	0.1500	0.0065	-0.4959

Bi-variate analysis : maximum rainfall intensity (imax) and maximum wind speed (vmax)

TC Rainfall Model: vmax & imax

Bi-variate analysis : maximum rainfall intensity (imax) and maximum wind speed (vmax)

Copula models: a multivariate analysis method used for hydrologic analysis, that allows to describe the dependence between multi variables.

Joint cumulative function of any continuous random variables (X,Y) can be written as:

$$H(x, y) = C[F(x), G(y)]$$

Copula: $C(u, v) = H[F^{-1}(u), G^{-1}(v)]$

MvCAT (Sadegh et al., 2017): Multivariate Copula Analysis Toolbox

- Fit the marginal distribution families to variables
- Fit 24 different copula families and rank the copula based on the performance metrics:
- Maximum likelihood, NSE, RMSE, Bayesian Information Criterion (BIC) and Akaike Information Criterion (AIC) → ***Provide the best copula fit to given data***

TC Rainfall Model: Equation

Radial rainfall profile form TCR model

Hypothesis: The location of vmax is same as the location of imax

Holland model

$$V_g(R) = \left(vmax * \frac{\left(\frac{RMW}{R}\right)^{b_s}}{\exp\left(\left(\frac{RMW}{R}\right)^{b_s}\right)} \right)^{x_n}$$

TCR model

$$I_g(R) = \left(imax * \frac{\left(\frac{RMW}{R}\right)^{b_s}}{\exp\left(\left(\frac{RMW}{R}\right)^{b_s}\right)} \right)^{x_n}$$

Copula simulation
Conditionally sampled

Add the effects from translation speed (TS)

$$V(\mathrm{r}) = V_g(R) + RMW \cdot R/(RWM^2 + R^2)TS$$

(Jelesnianski, 1966; Rego and Li, 2010; Wu et al., 2018)

$$I(\mathrm{r}) = I_g(R) + RMW \cdot R/(RWM^2 + R^2)TS$$

Fitted coefficients in the model : b_s and x_n are shape and scaling parameters estimated from observations

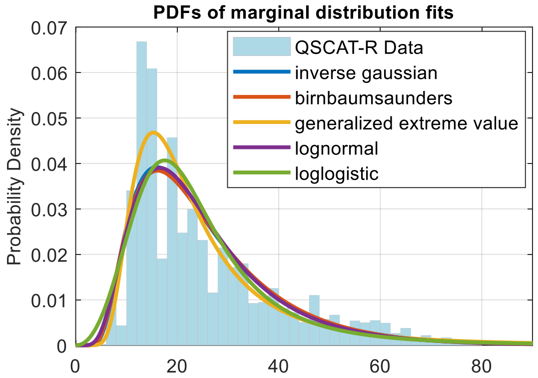
$$b_s = \frac{V_{max}^2 \rho_s e}{100(p_{env} - p_c)}$$

Suggested by Holland (1980; 2008; 2010)

$$b_s = a \cdot I_{max}^b \cdot \rho_s^c \cdot (p_{env} - p_c)^d$$
$$x_n = a \cdot I_{max}^b$$

TC Rainfall Model: Overall Procedure

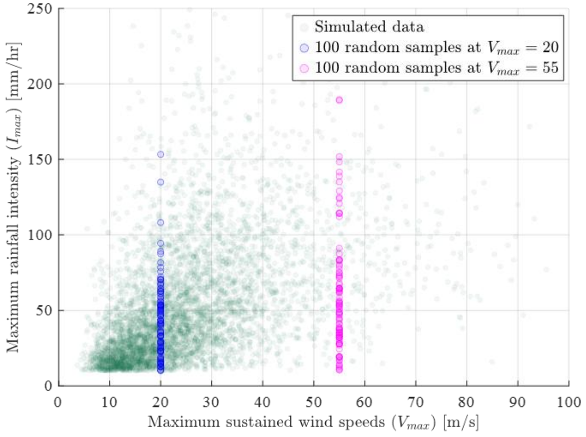
2



Maximum sustained wind speed (vmax)

✓ **Inverse Gaussian distribution**

4



1. Collect vmax and imax (QSCAT-R dataset)

2. Fit marginal distribution of vmax and imax

3. Find the best-fitting copula

4. Generate imax from copula → get conditionally sampled imax based on percentile

5. Validated **Radial rainfall profile**

Test the fit (Optimization) → 5 ← Tune the parameter bs, xn

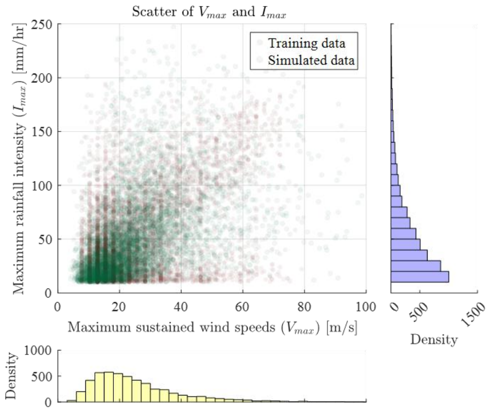
✓ **Frank Copula** 3

Joint distribution: $H(x,y) = C[F_X(x), F_Y(y)]$

Copula: $C(u,v) = H\left[F_X^{-1}(u), F_Y^{-1}(v)\right]$

$$C(u,v) = -\frac{1}{\theta}\ln\left[1 + \frac{(e^{-\theta u}-1)(e^{-\theta v}-1)}{e^{-\theta}-1}\right] \quad (\theta \in R\backslash 0)$$

Rank	Max-Likelihood	AIC	BIC
1	Frank	Frank	Frank
2	Nelsen	Nelsen	Nelsen
3	Roch-Alegre	Roch-Alegre	Roch-Alegre
4	Plackett	Plackett	Plackett
5	Gaussian	Gaussian	Gaussian
6	BB1	BB1	BB1
7	Tawn	Tawn	Tawn
8	Clayton	Clayton	Clayton
9	BB5	Galambos	Galambos
10	Galambos	BB5	BB5
11	Gumbel	Gumbel	Gumbel
12	AMH	AMH	AMH
13	Marshal-Olkin	Marshal-Olkin	Marshal-Olkin
14	Raftery	Raftery	Raftery
15	Burr	Burr	Burr
16	Fischer-Hinzmann	Fischer-Hinzmann	Fischer-Hinzmann
17	Cuadras-Auge	Cuadras-Auge	Cuadras-Auge
18	Shih-Louis	Shih-Louis	Shih-Louis
19	Linear-Spearman	Linear-Spearman	Linear-Spearman
20	Joe	Joe	Joe
21	FGM	FGM	FGM
22	Fischer-Kock	Fischer-Kock	Fischer-Kock
23	Cubic	Cubic	Cubic
24	Independence	Independence	Independence



Application to Compound flood: Hurricane Rita

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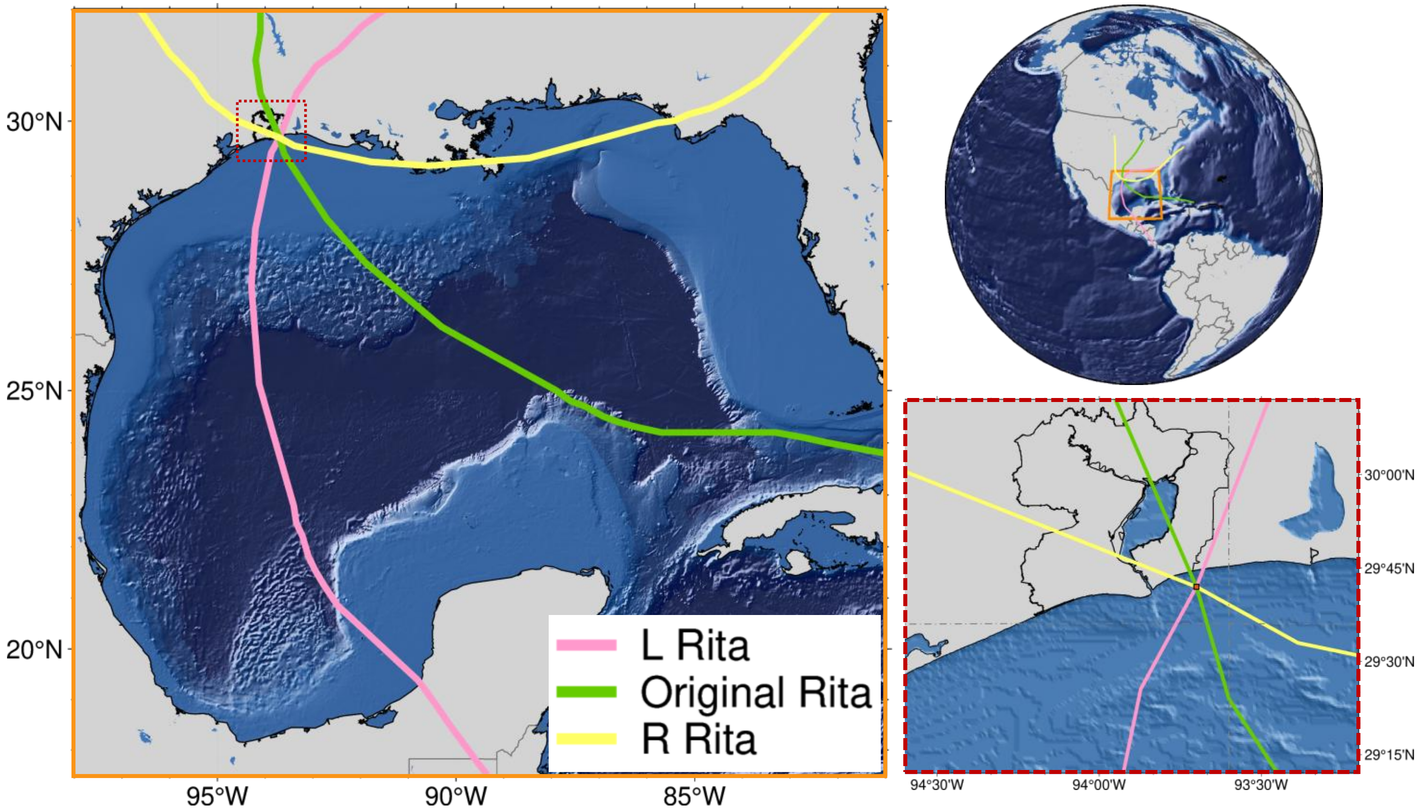
■ Flood Scenarios Different TC paths and varying external forcings

Model case: Hurricane Rita (2005) and synthetic tracks

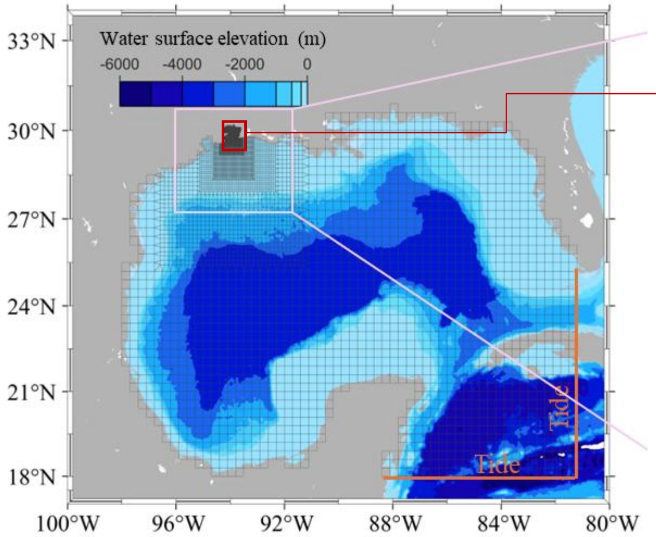


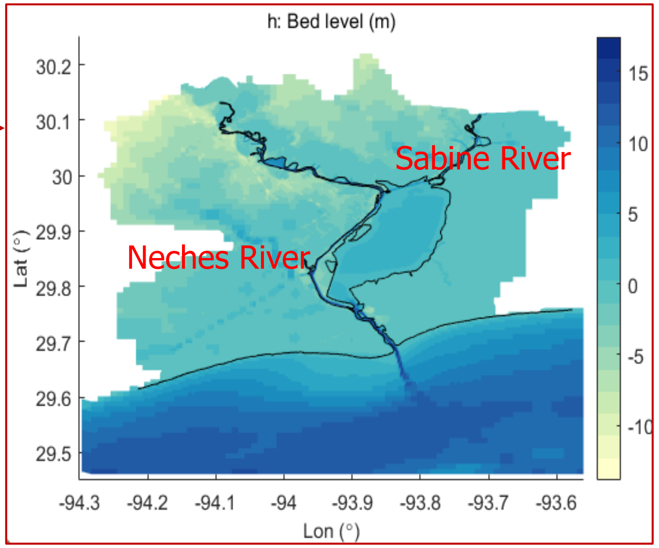
3 different tracks and 3 difference drivers

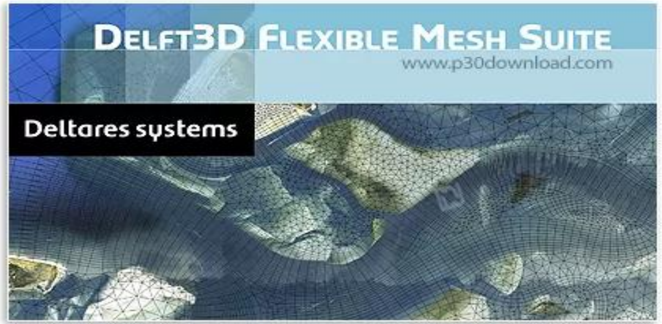
No.	TC track	External forcing
1	Original Rita	Compound (All)
2		Tide & Surge only
3		Rainfall only
4	Left-shifted track L Rita (-45 deg rotation)	Compound (All)
5		Tide &surge only
6		Rainfall only
7	Right-shifted track R Rita (45 deg rotation)	Compound (All)
8		Tide &surge only
9		Rainfall only

Application to Compound flood: Grid Set-up

Sabine-Neches River Estuary, TX

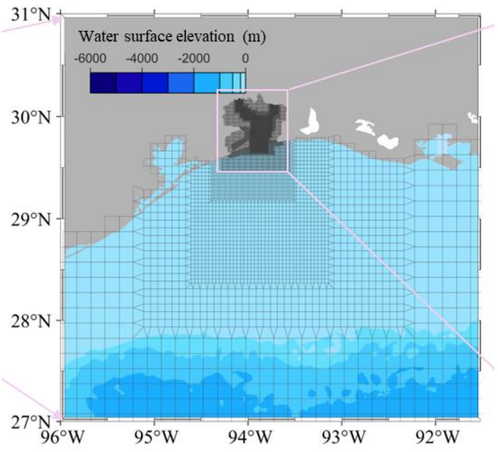


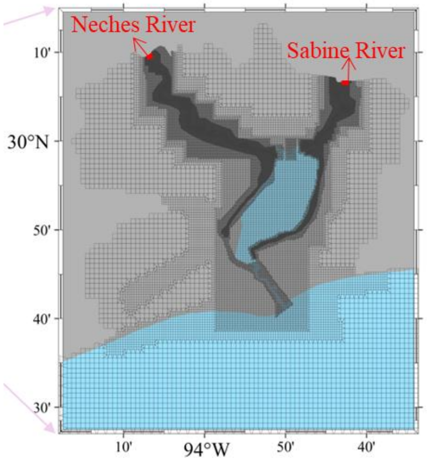




Maymandi, N., Hummel, M. A., & Zhang, Y. (2022), WRR.

Unstructured Grids: 25m – 30km (Cover entire Gulf of Mexico)

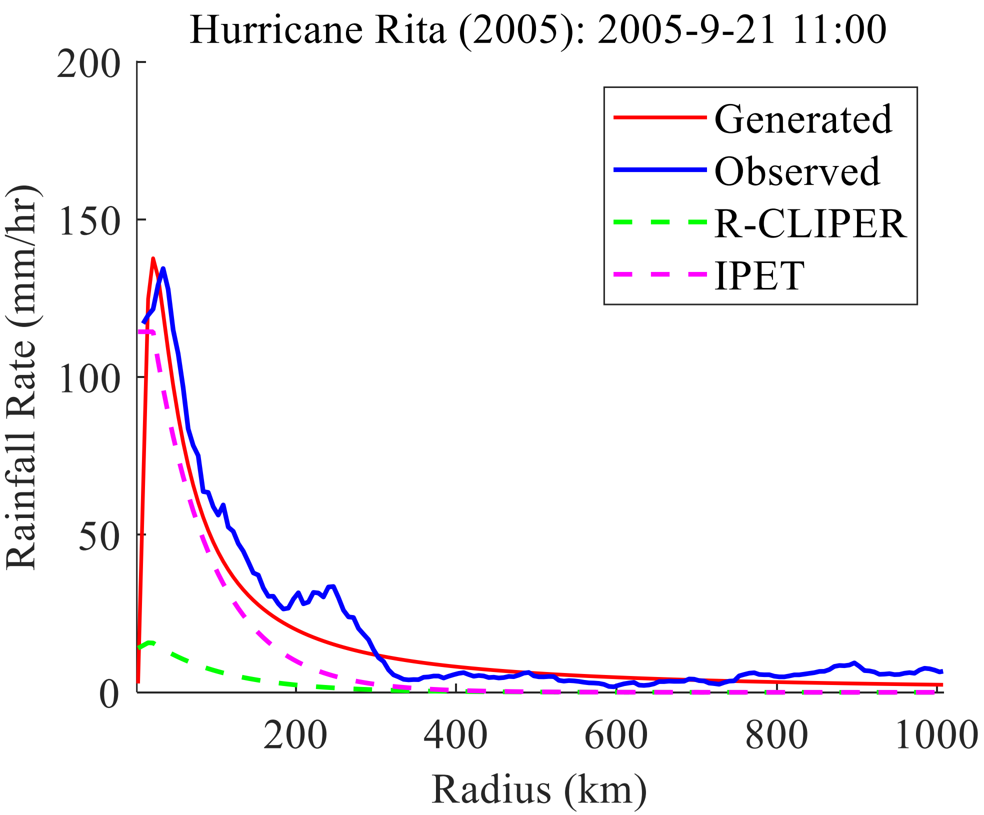


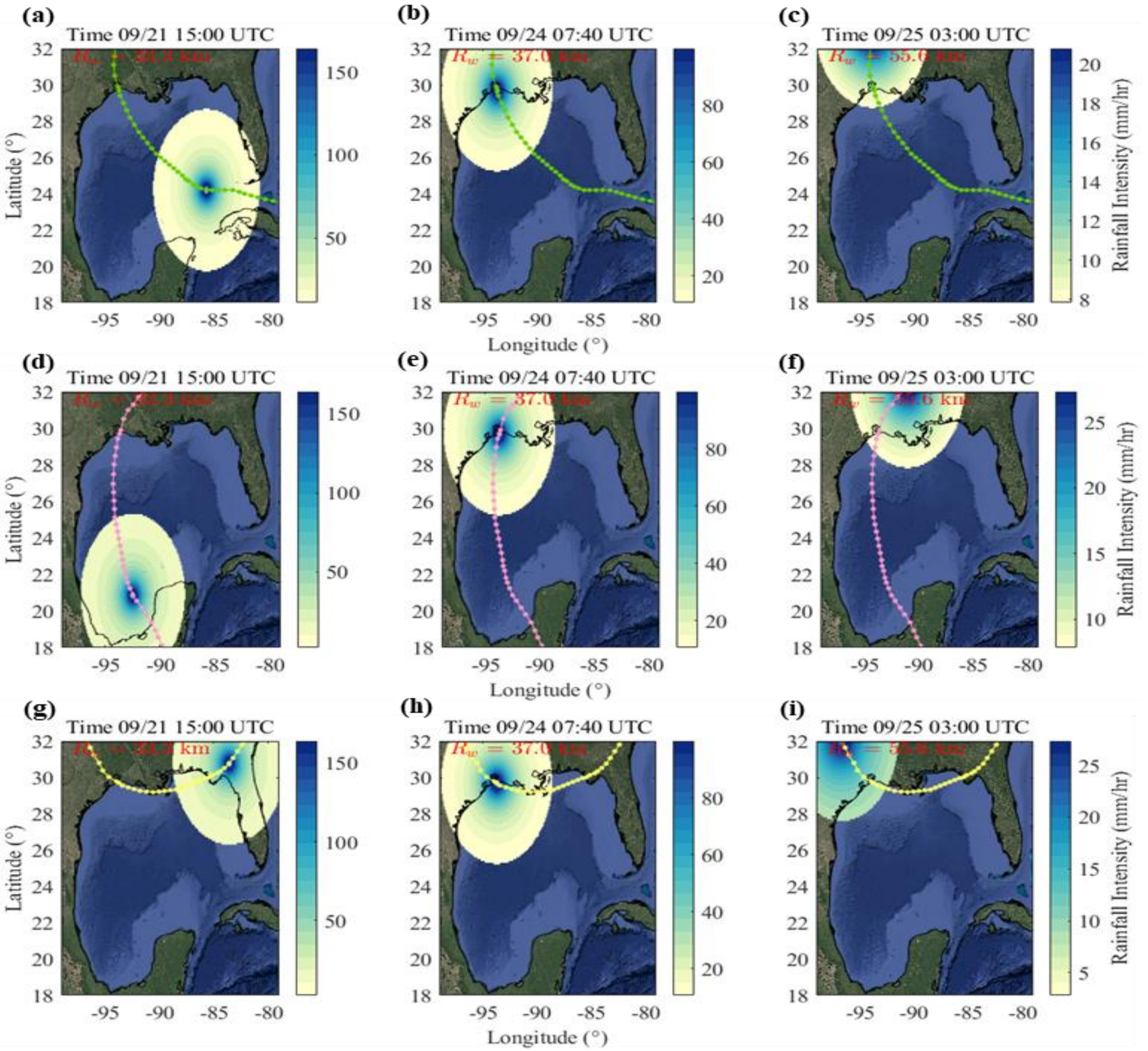


Application to Compound flood: TC Rainfall

■ Rainfall Generation

Using the developed TC radial rainfall model





Application to Compound flood: Metric

Evaluating the contribution of different forcing to peak water levels using the concept of disturbance (D) proposed by Huang et al. (2021)

$$D = \begin{cases} \eta, & h \geq 0 \ (wet\ area) \\ \eta + h, & h < 0 \ (dry\ area) \end{cases}$$

inundation depth on land

where η is the water surface elevation and *h* is the bed level (positive downward).

t_{peak}: the time of maximum water level in the compound model

$D_{tide\,\&\,surge}$, D_{rain} : disturbances defined at t_{peak}

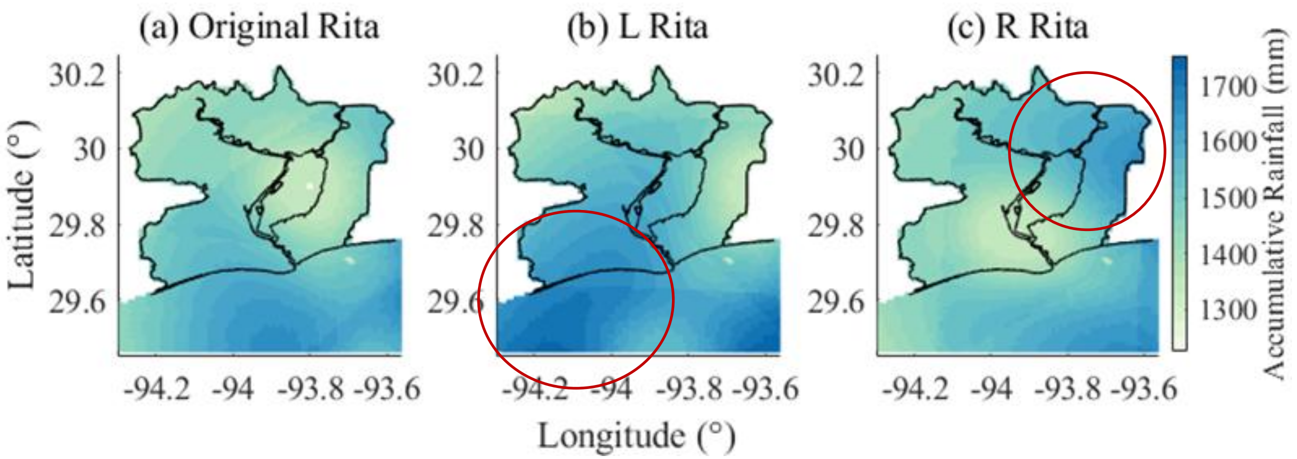
Contribution of the any forcing component: C

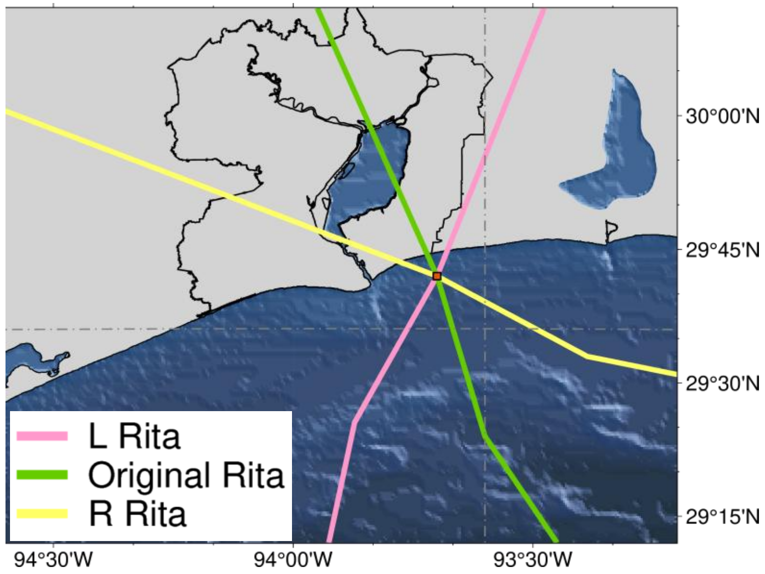
$$C_{rain} = \frac{D_{rain}}{D_{compound}} \times 100\ (\%)$$

Application to Compound flood: TC Rainfall

Result

Comparison of accumulated rainfall (AR)





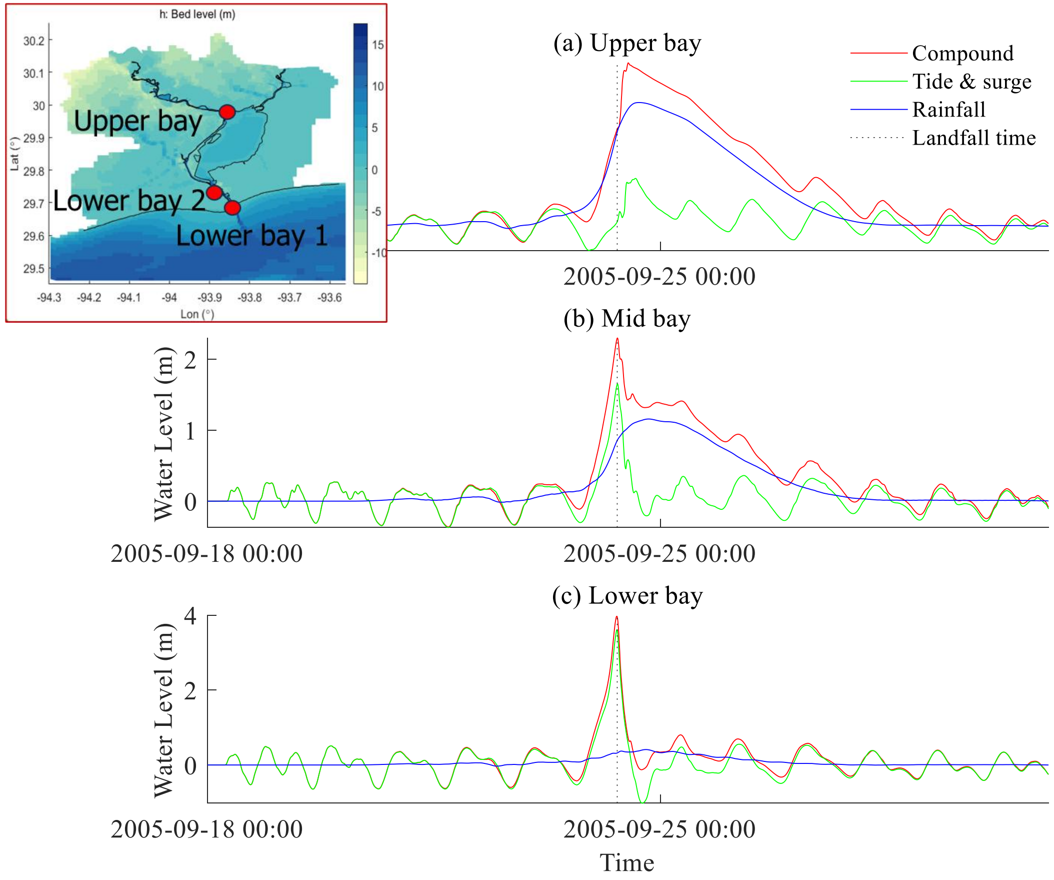
- Spatial Difference: Path shifts lead to distinct rainfall patterns across the basin.
- L Rita produces the highest accumulated rainfall, mainly in the western basin.
- R Rita shows the highest rainfall in the eastern–northern basin.

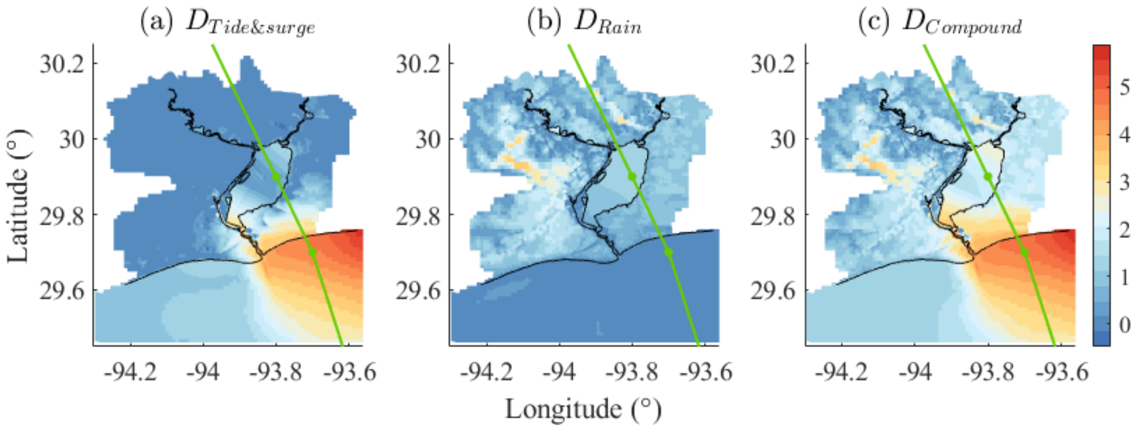
Result: Original Rita

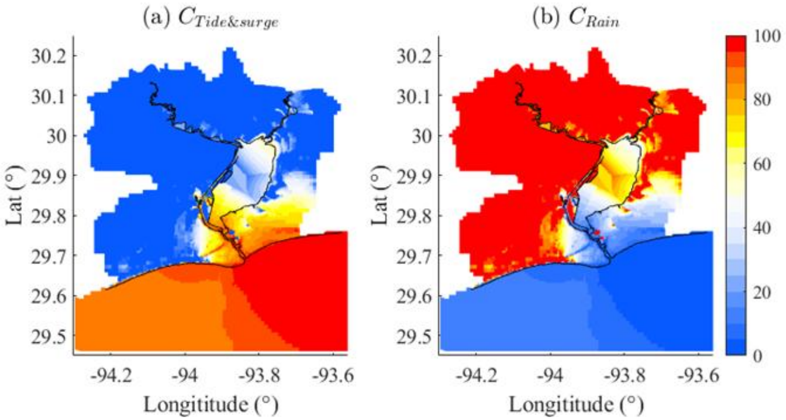
■ Result

Original Rita

Rainfall drives flooding in upper/mid bay, while surge dominates the lower bay.





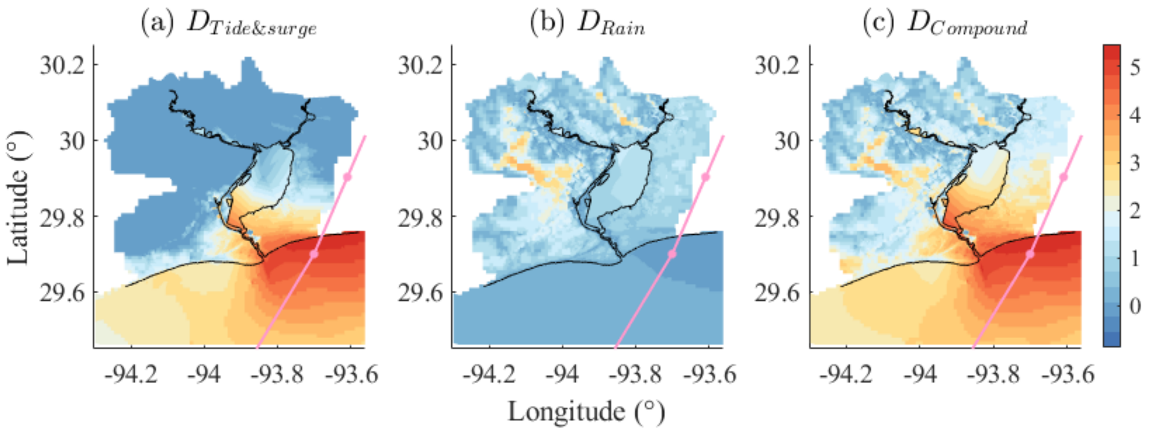


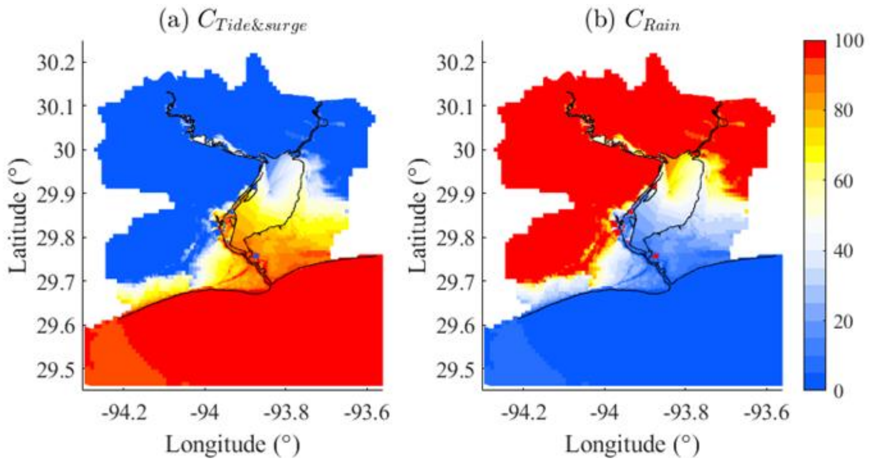
Rainfall dominates the upper and mid bay, while tide & surge dominate the lower bay.

Result: L & R Rita

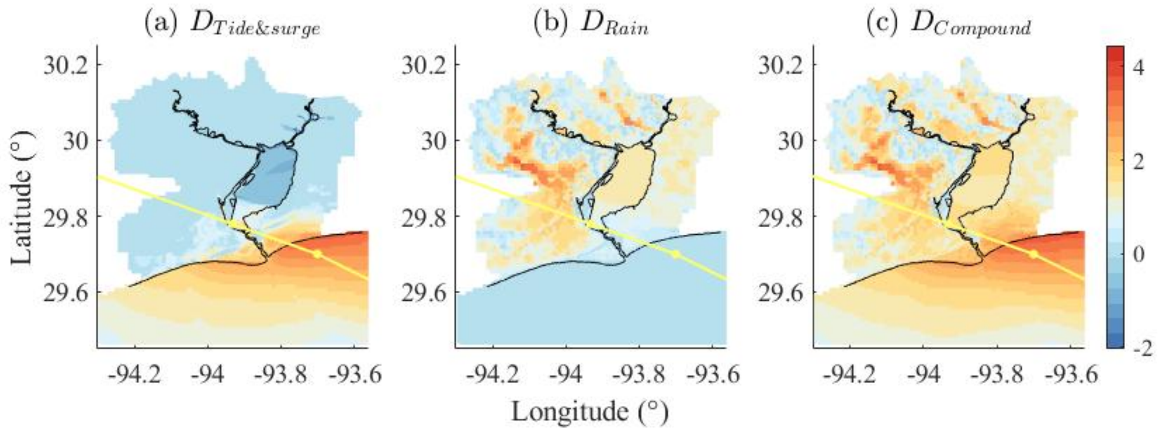
Result

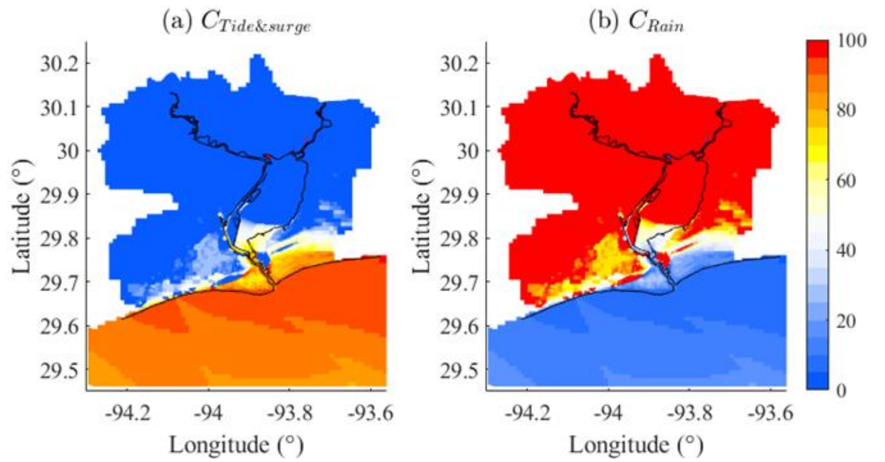
L Rita





R Rita





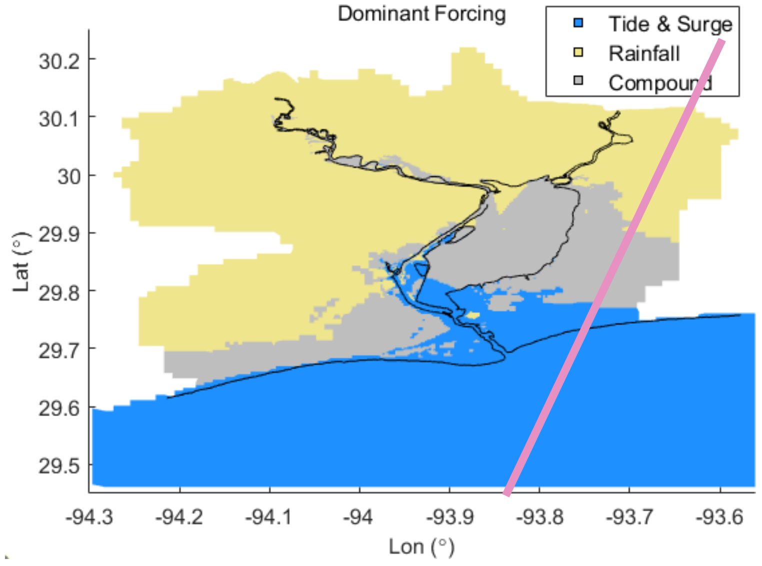
Changing the TC track substantially modifies how rainfall and surge contribute to flooding across space.

Result: Compound flood

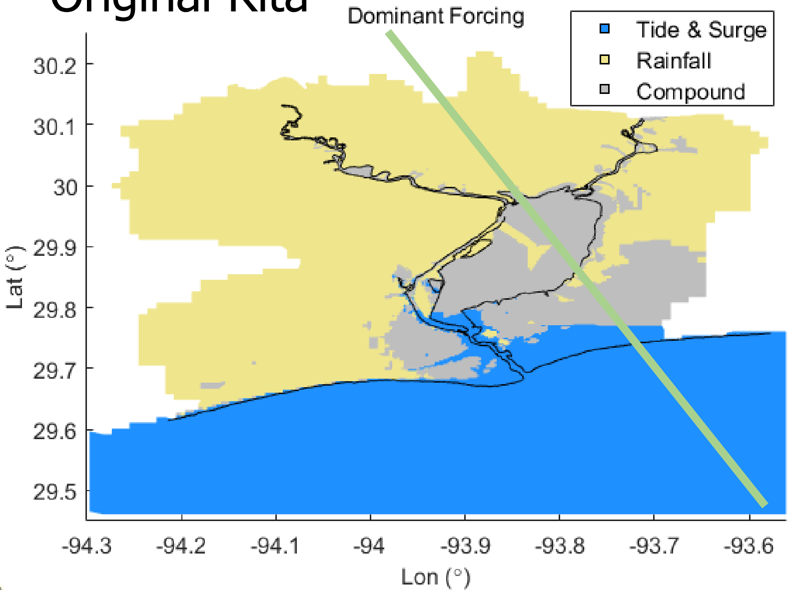
Area of dominant forcing

Areas in blue : dominated by tide and surge,
Areas in yellow : dominated by rainfall.
Areas in gray : no single forcing contributes more than 80% to the peak water levels, suggesting the potential for compound effects.

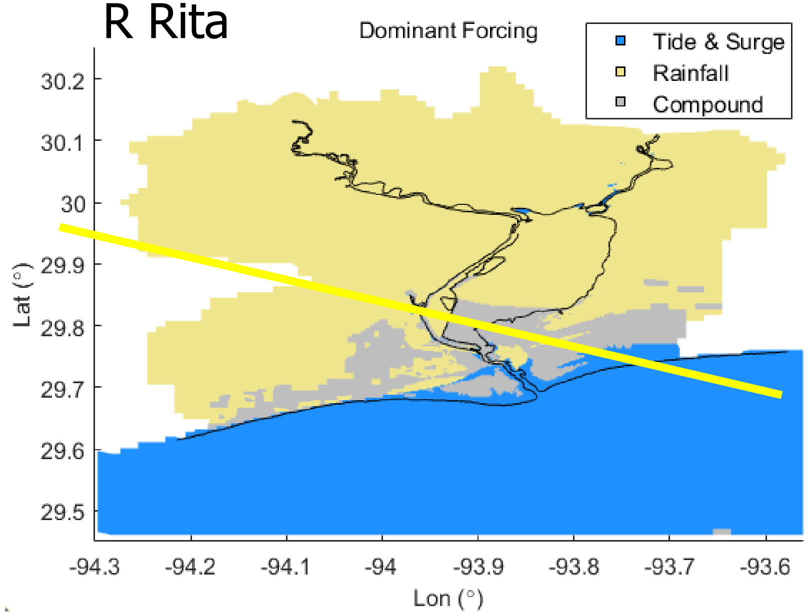
L Rita



Original Rita



R Rita



'Compound' dominates the area most

Rainfall dominates the area least

Tide & surge affect the most area

Compound affect most of the river channel

Compound dominates the least area

Rainfall dominates the most area

Conclusions

1. Parametric model for generating the TC rainfall

- Constructed radial rainfall profiles using a parametric model analogous to the Holland model by considering the relationship between imax and vmax
- Enhanced the performance of the model by adding translation effect and optimal sampling procedure

2. Compound flood induced by different TC rainfall

- TC from the Left (L Rita):
  - ➢ Dominated by storm surge, with rainfall affecting only upstream areas.
  - ➢ Extensive compound effects along the coastline and lower bay.
- TC Perpendicular to the Coast (Original Rita):
  - ➢ Balanced impact from rainfall and storm surge.
  - ➢ Compound flooding in river channels and upper bay areas.
- TC from the Right (R Rita):
  - ➢ Rainfall-driven flooding is the most extensive, covering land, rivers, and bays.
  - ➢ Less influence from storm surge and fewer compound effects.

Thank you for attention!

Q&A Email: sson@korea.ac.kr

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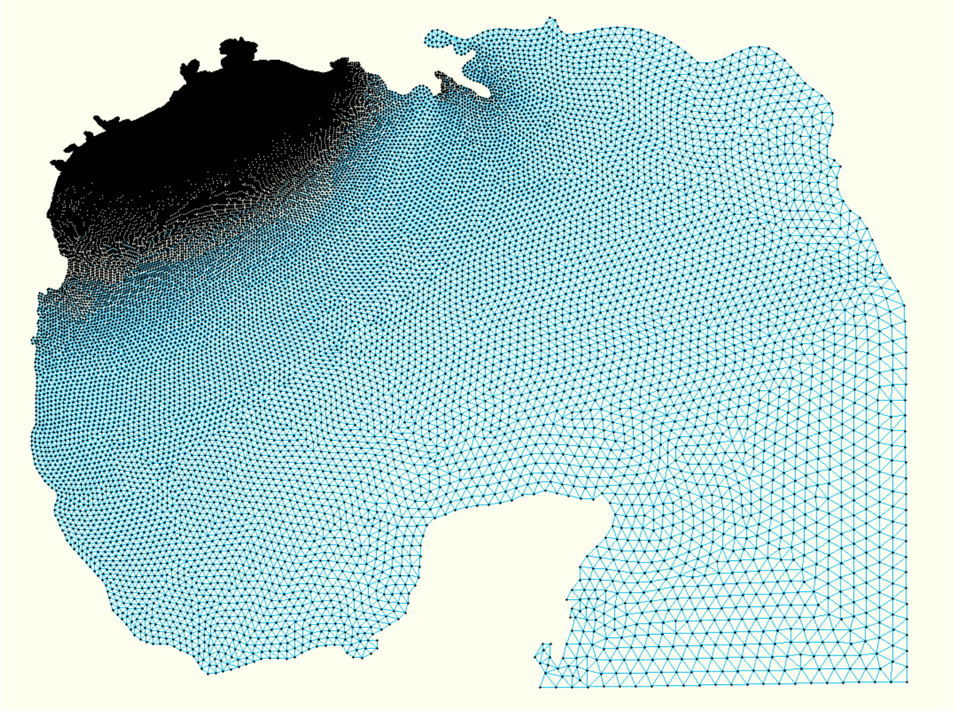
Future Work

1. Parametric model for generating the TC rainfall

- Improve the accuracy of the model (total rainfall)
- other datasets
- variability over space and time
- consider other TC track characteristics (e.g. pressure)
- difference from the surface characteristics (i.e., sea and land)
- …



2. Compound flood induced by different TC rainfall

- Validation with observations
- Apply a model with high resolution grid
- More TC synthetic tracks (translation speed, intensity…)
- …